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(54) Title: SOLID OXIDE REGENERATIVE FUEL CELL FOR AIRPLANE POWER GENERATION AND STORAGE

(57) Abstract: A solid Oxide Regenerative Fuel Cell (SORFC) or a Solid Oxide Fuel Cell (SOFC) is incorporated into an electrically powered airplane to provide either regenerative or primary electrical energy. The SORFC, the SOFC, or any other suitable fuel cell within an airplane may also be used to heat payload or equipment within the airplane. The SORFC is not only capable of generating electrical energy from fuel and a suitable oxidizer, but can also generate fuel through electrolysis of oxidized fuel. Thus, the SORFC system powering an airplane can obtain oxygen oxidant reactant from the air and avoid the complexity, weight, volume, and cost associated with oxygen storage.

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## Solid Oxide Regenerative Fuel Cell For Airplane Power Generation and Storage

### BACKGROUND OF THE INVENTION

[0001] The invention generally relates to the fuel cells, and specifically to use of a solid oxide fuel cell system as an energy converter in an airborne vehicle, such as in an airplane.

[0002] A solid oxide fuel cell (SOFC) is an electrochemical device that converts chemical energy directly into electrical energy. A Solid Oxide Regenerative Fuel Cell (SORFC) is an electrochemical device that converts chemical energy directly into electrical energy and subsequently reconverts electrical energy back to the original chemical energy. This device differs significantly from rechargeable batteries in that the chemicals are stored outside of the SORFC converter. The SORFC system has many building electrical energy storage applications that cannot be satisfied by batteries. For example, a SORFC system for building power generation is discussed in the Proceedings of the 2001 DOE Hydrogen Program Review NREL/CP-570-30535.

### BRIEF SUMMARY OF THE INVENTION

[0003] In one preferred aspect of the present invention, there is provided a solid oxide fuel cell adapted to power an airborne vehicle.

[0004] In another preferred aspect of the present invention, there is provided an electrically powered airplane, comprising an airplane body, a solid oxide fuel cell adapted to power the airplane, and a fuel storage vessel adapted to provide fuel to the solid oxide fuel cell.

[0005] In another preferred aspect of the present invention, there is provided an electrically powered airplane, comprising an airplane body, a fuel cell adapted to power the airplane and to heat remotely located payload or

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equipment in the airplane body, and a fuel storage vessel adapted to provide fuel to the solid oxide fuel cell.

[0006] In another preferred aspect of the present invention, there is provided a solid oxide fuel cell system, comprising a first means for providing oxygen ion conduction to generate a potential difference between a fuel electrode and an oxygen electrode, and a second means for providing electric power to an airborne vehicle from the potential difference.

[0007] In another preferred aspect of the present invention, there is provided a method of generating power in an airborne vehicle, comprising providing a fuel and an oxidizer to a solid oxide fuel cell, and providing electrical power from the fuel cell to a motor propeller system of the airborne vehicle.

[0008] In another preferred aspect of the present invention, there is provided an SORFC power generation system, comprising at least one SORFC cell, a fuel storage vessel, an oxidizer inlet, an oxidized fuel storage vessel, and a first means for (a) separating partially regenerated fuel provided from at least one SORFC cell into regenerated fuel and oxidized fuel, for directing the regenerated fuel into the fuel storage vessel and for directing oxidized fuel back into the at least one SORFC cell, and (b) separating partially oxidized fuel provided from the at least one SORFC cell into fuel and oxidized fuel, for directing the fuel back into the at least one SORFC, and for directing oxidized fuel into the oxidized fuel storage vessel.

#### **BRIEF DESCRIPTION OF THE DRAWINGS.**

[0009] Figure 1 is a schematic illustration of SORFC system in solar powered high altitude airplane.

[0010] Figure 2 is a schematic illustration of SOFC system in electrically powered high altitude airplane.

[0011] Figure 3 is a schematic illustration of SORFC system providing electrical power and heat in solar powered high altitude airplane.

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[0012] Figure 4 is a schematic illustration of SOFC system providing electrical power and heat in electrically powered high altitude airplane.

[0013] Figure 5 is a schematic illustration of basic elements of SORFC in discharge mode.

[0014] Figure 6 is a schematic illustration of basic elements of SORFC in charge mode.

[0015] Figure 7 is a three dimensional view of planar SORFC stack.

[0016] Figure 8 is a schematic illustration of manifolded SORFC stack.

[0017] Figure 9 is a schematic illustration of SORFC system in discharge mode.

[0018] Figure 10 is a schematic illustration of SORFC system in charge mode.

[0019] Figure 11 is a schematic illustration of SORFC system components in discharge mode.

[0020] Figure 12 is a schematic illustration of SORFC system components in charge mode.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0021] The present inventors have realized that a solid oxide fuel cell, such as the SOFC and the SORFC, has unique properties that make it advantageous as an energy generation and storage device in an airborne vehicle, such as an airplane. The present inventors have realized that the SORFC does not require an independent source of oxygen or pure water when the SORFC is used for energy generation or storage for an airborne vehicle that operates in Earth's atmosphere. The SORFC system is distinct from other hydrogen-oxygen (or hydrocarbon-oxygen) regenerative fuel cell systems in that no water (or other oxidized fuel) is lost from the cell with the air or oxygen oxidant discharge. Therefore the SORFC can be operated open loop on the oxygen

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oxidant side without requiring any makeup of any reactants or process chemicals. In contrast, other regenerative fuel cells that operate with an open oxygen oxidant loop must have an independent source of pure water, as process water is lost with the air oxygen oxidant discharge. Thus, the SORFC system operating in an airborne vehicle in the earth's atmosphere can obtain oxygen oxidant reactant from the air and avoid the complexity, weight, volume, and cost associated with oxygen oxidant storage.

#### **[0022] The First Preferred Embodiment**

[0023] An airborne vehicle is a vehicle capable of flying. A preferred type of airborne vehicle that uses the SORFC is a high altitude solar powered unmanned airplane. This airplane is used as a stationary platform for commercial communications, military surveillance or as a weapon platform. The high altitude solar powered unmanned airplane uses solar generated electricity to drive electric motor propeller and electrolyze water in the SORFC during the daylight and uses the stored fuel to generate electric power in the SORFC during the nighttime to drive an electric motor propeller system. Using the SORFC eliminates the need to store oxygen, as none of the process water is lost. This greatly increases the capability of the airplane due to the significant weight reduction. However, the SORFC may be used in any other type of airborne vehicle, such as manned airplanes, fuel powered airplanes or even helicopters.

[0024] A hydrogen/oxygen (i.e., hydrogen fuel, oxygen or air oxidizer) SORFC is preferred for use in the airborne vehicle. However, other SORFC types, such as hydrocarbon/oxygen types may be used instead. The use of a hydrogen/oxygen SORFC within the high altitude solar powered unmanned airplane provides the airplane with the capability to operate at high altitude for many months only returning to the ground for maintenance. The ability to use atmospheric oxygen (i.e., air) instead of stored oxygen saves sufficient mass to allow the airplane to fly at higher altitude and/or to carry an increased payload. The airplane, with a wing span in the range of 100 to 500 feet, such

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as about 200 feet and a mass of about 1000 to 3000 pounds, such as 1500 pounds, will generally fly above the weather at an altitude of between 45,000 to 90,000 feet. At these altitudes the airplane can be on station 24 hours a day without weather concerns. The airplane can loiter over a point on the ground or it can be relocated to a new location in the range of about 10-50 mph, such as 30 miles per hour. The total DC electrical power required for maintaining altitude is in the range of 7 to 9 kW.

[0025] In one aspect of the first embodiment, the airplane is powered by one SORFC system. However, in a preferred aspect of the first embodiment, the airplane is powered by multiple smaller SORFC systems distributed along the length of the wing(s). This results in an advantage in mass distribution and redundancy. The generally accepted mass allocation for the energy storage system for the high altitude solar powered unmanned airplane is about 400 pounds of which about 150 pounds is allocated to the SORFC.

[0026] Other potential regenerative fuel cell systems, such as the PEM regenerative fuel cell, produce the fuel cell discharge chemical byproduct (water) on the oxidant side of the cell. To open the oxygen oxidant system loop to take advantage of the mass savings associated with oxidant storage elimination, the byproduct water would be lost and the regenerative nature destroyed. Even if most of the byproduct water from an open loop oxidant could be captured, there are other deficiencies in the PEM open loop oxidant type of regenerative fuel cell. First, some water make up would be required as not all of the byproduct water could be captured. Second, the water vapor that is discharged would provide a condensation trail to easily identify the location of the airplane and this water could interfere with sensitive onboard sensors. Third, the altitude at which the airplane flies is within the range of maximum ozone concentration and the ozone ingested into the cell oxygen oxidant chambers is known to degrade organic species such as the organic PEM electrolyte.

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[0027] The SORFC system overcomes the deficiencies of the hydrogen/oxygen PEM open loop oxidant regenerative fuel cell. First, a hydrogen ion is transported in the PEM fuel cell. In contrast, in the SORFC, an oxygen ion is transported across the electrolyte. Thus, the byproduct water is formed on the fuel side of the electrolyte in the SORFC. The only chemical produced or consumed within the SORFC oxidant chamber is oxygen and no water is lost from the open loop oxidant. This eliminates water make up, detectable condensation trails, and interference with sensors. Second, since no organic materials are preferably used within the SORFC stack, the hardware is immune to ozone degradation.

[0028] Figure 1 illustrates a SORFC system within a high altitude solar powered unmanned airplane according to a preferred aspect of the first embodiment. Preferably, all of the airplane power comes from solar radiation. However, an alternative or an additional power source may also be used. The airplane contains a body which may include a fuselage as well as a wing structure (not shown for clarity). The top surface of the airplane's large wing structure is mostly covered with photovoltaic cells to form a solar array 700. The solar array 700 may also be located on other parts of the airplane. This array converts the solar radiation into DC electricity. During the daytime, when solar radiation is available, a portion of the DC electricity is delivered to the motor propeller system 740 (i.e., an electrical motor which rotates the propeller) from the solar array 700 via electrical cable 720. This provides thrust to the airplane during the daytime. Of course the SORFC system can be used with other types of airplane propulsion systems, such as a ducted fan, etc., and it also may be used on other types of airplanes.

[0029] Another portion of the DC electricity is delivered to the SORFC 240 from the solar array 700 via electrical cable 710. At the same time oxidized fuel (i.e., water) is delivered to the SORFC 240 from oxidized fuel storage vessel 260 via fluid conduit 290. Within SORFC 240, the water is electrolyzed using the DC electricity provided from array 700. The oxygen oxidant is discarded from the SORFC 240 via fluid conduit 310. For example, conduit

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310 may be an outlet pipe which vents oxygen into the atmosphere. The hydrogen (or hydrocarbon) fuel is delivered to fuel storage vessel 250 from SORFC 240 via fluid conduit 280. Ambient air, if needed for thermal control, is delivered to SORFC 240 via fluid conduit 300. Any thermal control air is discharged from SORFC 240 via fluid conduit 310 along with the generated oxygen oxidant.

[0030] During the nighttime, when solar radiation is not available, the previously generated hydrogen (or hydrocarbon) fuel is delivered to SORFC 240 from fuel storage vessel 250 via fluid conduit 280. Simultaneously, ambient air as the oxidant source is delivered to the SORFC 240 via fluid conduit 300. Within SORFC 240, DC electricity is generated and delivered to the motor propeller system 740 via electrical cable 730 to provide thrust to the airplane during the nighttime. Depleted air is discharged from the SORFC 240 via fluid conduit 310. The air oxidant source flow also serves as a thermal control fluid. The oxidized fuel (water) is delivered from the SORFC 240 to the oxidized fuel storage vessel 260 via fluid conduit 290.

#### [0031] Second Preferred Embodiment

[0032] In a second preferred embodiment of the present invention, a non-regenerative solid oxide fuel cell (SOFC) is used as a primary power source for an airborne vehicle, such as the high altitude unmanned airplane. In this embodiment, all the energy for the airplane comes from fuel carried onboard. For missions of only a few hours to a few days duration, the high-energy conversion efficiency of the SOFC combined with its ability to effectively use the high altitude air as the oxidant makes this approach advantageous.

[0033] The use of hydrogen as the fuel is preferred because it allows the airplane to maintain a stealth character as the oxidized fuel (water) is stored and the airplane retains a zero emission status. However, if desired, a conventional hydrocarbon fuel (such as propane) may be used instead if the stealth characteristics are not important in the airplane.

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[0034] As in the SORFC, the SOFC uses atmospheric air as the source of oxygen oxidant without compromising the stealth. The advantages of the SOFC compared to the open loop oxidant PEM fuel cell include the lack of a water vapor condensation trail with its further interference with onboard sensors and the tolerance to atmospheric ozone.

[0035] Figure 2 illustrates a SOFC system within a high altitude unmanned airplane according to a preferred aspect of the second embodiment. Fuel (preferably hydrogen) is delivered from fuel storage vessel 250 to the SOFC 750 via fluid conduit 280. Simultaneously, ambient air oxidant oxygen is supplied to SOFC 750 via fluid conduit 300. Within SOFC 750, reactions produce DC electricity and oxidized fuel (water). The oxidized fuel is delivered from the SOFC 750 to the oxidized fuel storage vessel 260 via fluid conduit 290. If stealth characteristics are not important in the airplane, then the oxidized fuel may be vented into the atmosphere and the storage vessel 260 and conduit 290 may be omitted. The depleted oxidizer (i.e., oxygen depleted air) is vented into the atmosphere through conduit 310. The DC electricity is delivered from the SOFC 750 to the motor propeller system 740 via electrical cable 760 providing thrust for the airplane until the fuel is exhausted.

[0036] **The Third Preferred Embodiment**

[0037] In a third preferred embodiment a SORFC or a SOFC system is not only used to provide a high altitude solar powered unmanned airplane with electrical energy, but also provides heat for thermal conditioning of airplane systems or payload. SORFC and SOFC systems operate at elevated temperatures and generate heat during operation. Part of this heat can be harnessed and transported to airplane systems or payload that require heating. For example, for an airplane operating at 66,000 ft altitude, the ambient air temperature is approximately -55°C. Some of the equipment within the airplane should be kept at temperatures above this ambient temperature. This equipment may be heated using electric heating.

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However, electric heating adds additional power requirements to the airplane power supply system which can result in additional mass. Some of this additional mass can be eliminated if a heat transport loop is provided which transports thermal energy from the SORFC or SOFC to the equipment or payload that needs to be heated. Alternatively, in a manned airplane, the occupant compartment may be heated using heat from the SOFC or SORFC.

[0038] Figure 3 illustrates an SORFC system within a high altitude solar powered unmanned airplane that also supplies heat to airplane systems or payloads, according to a preferred aspect of the third embodiment. The system of Figure 3 is similar to that illustrated in Figure 1, except that the SORFC 240 is used to heat an airplane system or payload 810 that is located in the airplane body remote from the SORFC system. Preferably all of the airplane power comes from solar radiation. The top surface of the airplane's large wing structure is mostly covered with photovoltaic cells to form a solar array 700. This array converts the solar radiation into DC electricity. During the daytime, when solar radiation is available, a portion of the DC electricity is delivered to the motor propeller system 740 from the solar array 700 via electrical cable 720. This provides thrust to the airplane during the daytime. Another portion of the DC electricity is delivered to the SORFC 240 from the solar array 700 via electrical cable 710. At the same time oxidized fuel (water) is delivered to the SORFC 240 from oxidized fuel storage vessel 260 via fluid conduit 290. Within SORFC 240 the water is electrolyzed using the DC electricity. The oxygen oxidant is discarded from the SORFC 240 via fluid conduit 310. The hydrogen fuel is delivered to fuel storage 250 from SORFC 240 via fluid conduit 280. Ambient air, if needed for thermal control, is delivered to SORFC 240 via fluid conduit 300. Any thermal control air is discharged from SORFC 240 via fluid conduit 310 along with the generated oxygen oxidant.

[0039] During the nighttime, when solar radiation is not available, the previously generated hydrogen fuel is delivered to SORFC 240 from fuel storage 250 via fluid conduit 280. Simultaneously, ambient air as the oxidant

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source is delivered to the SORFC 240 via fluid conduit 300. Within SORFC 240 DC electricity is generated and delivered to the motor propeller system 740 via electrical cable 730 to provide thrust to the airplane during the nighttime. Depleted air is discharged from the SORFC 240 via fluid conduit 310. The air oxidant source flow also serves as a thermal control fluid. The oxidized fuel (water) is delivered from the SORFC 240 to the oxidized fuel storage vessel 260 via fluid conduit 290.

[0040] The SORFC generates heat during charge and discharge operation. A heat transport loop 800 transports heat from the SORFC to the equipment (i.e., electronics, etc.) or payload 810 in need of heat. The heat transport loop 800 may comprise pipe(s) or duct(s) filled with a heat transfer medium, such as a gas or liquid. Preferably, the loop 800 uses air as the heat transfer medium. Cooling air is blown past or adjacent to the hot fuel cell stack 240 through the loop 800. The air absorbs heat as it is passed through loop 800 and the warmed air is guided toward or adjacent to the remotely located equipment or payload 810 that needs to be heated. Thus, the loop 800 provides heat to equipment or payload that would not ordinarily be heated by the SORFC (i.e., "remotely" located payload or equipment is payload or equipment that would not be substantially heated by the SORFC but for the loop 800). The loop 800 may be an open or a closed loop. The heat transport loop can also operate with a liquid or a two-phase re-circulation loop. Other modes of heat transfer, such as conduction or radiation can also be used.

[0041] Waste heat can also be used to heat payload or equipment 810 when a SOFC is acting as a primary power source for a high altitude airplane. Figure 4 illustrates a SOFC system within a high altitude unmanned airplane used to supply heat to airplane systems or payload. The SOFC system in Figure 4 is similar to the SOFC system shown in Figure 2, except for the presence of the heat transfer loop 800.

[0042] Fuel (hydrogen) is delivered from fuel storage vessel 250 to the SOFC 750 via fluid conduit 280. Simultaneously, ambient air oxidant oxygen is

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supplied to SOFC 750 via fluid conduit 300. Within SOFC 750, reactions produce DC electricity and oxidized fuel (water). The oxidized fuel is delivered from the SOFC 750 to the optional oxidized fuel storage vessel 260 via fluid conduit 290. The DC electricity is delivered from the SOFC 750 to the motor propeller system 740 via electrical cable 760 providing thrust for the airplane until the fuel is exhausted.

[0043] A heat transport loop 800 transports heat from the SOFC to the equipment or payload 810 in need of heat. The heat transport loop 800 may comprise pipe(s) or duct(s) through which a heat transfer medium travels, similar to that described with respect to the system of Figure 3. Heat transfer medium, such as cooling air, is blown past the hot SOFC stack 750, where the air absorbs heat. The warmed air is guided through the loop 800 to the equipment or payload 810 that needs to be heated. The heat transport loop can be open or closed loop and also operate with a liquid or a two-phase recirculation loop. Other modes of heat transfer, such as conduction or radiation can also be used. It should be noted that while SORFC and SOFC systems are preferred for providing heat in the airplane, other fuel cell systems, such as PEM fuel cell systems, may be used instead.

#### **[0044] The Fourth Preferred Embodiment**

[0045] Any type of SOFC or SORFC may be used to provide power and/or heating for an airborne vehicle of the first through third embodiments. A preferred SORFC system for use in the airborne vehicle is described below. However, it should be noted that the SORFC system described below may be used to power and/or heat objects other than an airborne vehicle, such as a ground based vehicle (i.e., automobile, etc.), water based vehicle (i.e., ship), a building or various devices requiring heat or power.

[0046] The SORFC is an electrochemical device based on a solid, oxygen ion conducting electrolyte, which is capable of generating electrical energy by oxidation of a fuel, and which is also capable of regenerating the oxidized fuel

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back into fuel. Figure 5 shows a functional schematic of a SORFC in "discharge" or "electricity generation" mode.

[0047] The SORFC 400 contains a solid electrolyte 100, a fuel electrode 110 and an oxygen electrode 120. The electrolyte 100 is an oxygen ion conducting material such as a ceramic material. Preferably, yttria stabilized zirconia (YSZ) is used, but other materials, such as gadolinia doped ceria or scandia doped zirconia can also be used. The oxygen electrode 120 is made from a material that can conduct electrons in an oxidizing environment. Two preferred materials are strontium doped lanthanum manganite (LSM) and platinum, which is often mixed with an oxygen ion conductor such as YSZ. Other materials capable of conducting electrons in an oxidizing environment can also be used.

[0048] In non-regenerative solid oxide fuel cells (SOFC), nickel YSZ mixtures are commonly used as fuel electrodes 110 for electrical energy generation. Nickel requires a reducing environment in order to work properly. In a SORFC, the fuel electrode 110 is exposed to a reducing environment during discharge, but is exposed to an oxidized fuel during charge operation. Therefore, materials capable of conducting electrons in an oxidizing environment should be used at the fuel electrode 110. Similarly to the oxygen electrode 120, platinum that is mixed with YSZ or LSM is preferably used as a fuel electrode 110 material. Other materials that are capable of conducting electrons in an oxidizing environment can also be used.

[0049] The fuel supply 130 reaches the fuel electrode side of the SORFC 400. The fuel 130 is preferably hydrogen, but other fuels, for example hydrocarbons or oxygenated hydrocarbons can also be used. An oxidizer 150, preferably air, reaches the SORFC on the oxygen electrode side. Other oxidizer, for example pure oxygen can be used. The fuel reacts with oxygen available at the fuel electrode 110 and thereby creates a low oxygen partial pressure on the fuel electrode 110 side of the cell.

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[0050] Electrically conductive electrodes 110 and 120 on both sides of the electrolyte 100 can provide and absorb electrons and thereby oxygen ions can be generated and consumed. The difference in partial pressure of oxygen between the fuel electrode 110 and the oxygen electrode 120 drives negatively charged oxygen ions from the oxygen electrode 120 through the electrolyte 100 to the fuel electrode 110. Thereby, negative electrical charge is transported from the oxygen electrode 120 to the fuel electrode 110. This charge transport generates an electrical potential difference between fuel electrode 110 and oxygen electrode 120, which can be used to drive an electrical circuit (not shown in Figures for clarity) connected to the SORFC via the fuel electrode electrical connection 122 and the oxygen electrode electrical connection 126.

[0051] Oxidized fuel leaves the SORFC in the oxidized fuel outflow 140. The oxidized fuel preferable consists of a mixture of water vapor and unreacted hydrogen, but other materials are also possible. Oxygen depleted oxidizer leaves the SORFC in the depleted oxidizer outflow 160. The oxygen depleted oxidizer is preferably air with a reduced oxygen content as compared to the oxidizer inflow 150, but other materials can also be used.

[0052] Figure 6 illustrates a functional schematic of the SORFC 400 in "electrolyzer" or "charge" mode. Oxidized fuel reaches the fuel electrode 110 at the oxidized fuel inflow 170. The oxidized fuel is preferably water vapor, but other materials, for example a mixture of carbon oxides and water vapor can also be used. An electrical potential is applied through the fuel electrode electrical connection 122 and oxygen electrode electrical connection 126. This creates a driving force to electrolyze the oxidized fuel 170 at the fuel electrode 110 and transport the oxygen through the electrolyte 100 to the oxygen electrode 120. As in the discharge mode, the transfer of oxygen from the fuel electrode 110 through the electrolyte 100 to the oxygen electrode 120 occurs in the form of oxygen ion transport.

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[0053] Regenerated fuel and residual oxidized fuel leave the SORFC at the regenerated fuel outflow 180. This mixture preferably consists of hydrogen and water vapor, but other materials are also possible. An optional oxygen electrode inflow 190 can be provided to the oxygen electrode 120. This optional oxygen electrode inflow 190 can, for example, provide temperature management of the SORFC, but can also serve other purposes and it may also be absent. Ambient air is a preferred material for the optional oxygen electrode inflow 190, but other materials can also be used. The regenerated oxidizer outflow 200 removes regenerated oxidizer and optional oxygen electrode inflow 190 from the cell. This regenerated oxidizer outflow preferably consists of pure oxygen or an oxygenair mixture, but other materials can also be used.

[0054] For practical use the SORFC can be packaged in a multi-cell system by stacking a number of the repeating elements 220 as shown in Figure 7. The amount of power available from an SORFC depends on the electroded area. Multi-cell systems provide for convenient packaging of large electroded areas.

[0055] Figure 7 illustrates an example for packaging of multiple SORFC. Here a planar electrolyte 100, with fuel electrode 110 and oxygen electrode 120 applied to either side of the planar electrolyte 100, is sandwiched between interconnect plates 210 thereby forming a stack. The elements shown in Figure 7 can be repeated many times to form a large SORFC stack. The interconnect plate 210 serves several functions. The interconnect plate 210 separates the gas volume adjacent to the fuel electrode 110 from the gas volume adjacent to the oxygen electrode 120. This separation avoids uncontrolled reaction or mixing of the gases on the two sides of each electrolyte 100. In SORFC, this separation is also important to avoid losses of the fuel or oxidized fuel, which would limit the useful life of the energy storage device. The interconnect 210 also provides a flow path for the gases on either side of the electrolyte. For example, the gas flow paths may comprise grooves in plate 210.

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[0056] Figure 7 illustrates a system with the fuel inflow 130 on the right side of the SORFC stack and the oxidized fuel outflow 140 on the left side of the stack. The oxidizer flow proceeds from the oxidizer inflow 150 on the back side of the stack to the depleted oxidizer outflow 160 on the front of the stack. This cross-flow configuration is one preferred flow path. Other preferred flow paths are co-flow where both gases stream in the same direction and counter flow where the two gases flow in opposite directions. The system can also be provided with other flow paths, for example paths based on circular stack geometries. The interconnect plate 210 can also provide an electrical current path within the stack. One preferred example is an interconnect 210 fabricated from an electrically conductive material. One side of interconnect 210 contacts a fuel electrode 110, and the other side contacts an oxygen electrode 120. Current flows through the interconnect 210 to the fuel electrode 110, through the electrolyte 100, through the oxygen electrode 120, and then through the next interconnect 210. This group of conducting elements can be repeated. One preferred material for the interconnect 210 is a metal which expands at the same rate as the electrolyte 100 during temperature changes, such as a metal felt described in U.S. provisional application serial number 60/357,636, filed February 20, 2002, incorporated herein by reference. Other examples are high temperature alloys, ferritic steels, or electrically conductive ceramics. Other materials can be used for the interconnect 210. For many of these materials surface coatings may be added in order to achieve a chemically stable system.

[0057] In a SORFC, both sides of the interconnect 210 need to be capable of operating in an oxidizing environment. In contrast, in a SOFC, the side of the interconnect 210 facing the fuel electrode 110 can be operated solely in a reducing environment which poses relaxed requirements for the interconnect 210.

[0058] The planar stacked electrolytes in Figure 7 are only one preferred example for packaging of SORFC. Other possibilities include, but are not limited to, cells in which the electrolyte is formed into tubes.

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[0059] Figure 7 does not show how the gases are manifolded in order to supply and remove gas from the repeating stack elements 220. Figure 8 presents one preferred example for external manifolding of the stack elements shown in Figure 7. The repeating elements 220 are mounted inside a circular cylinder 230. Gas distribution to the repeating elements 220 is provided in the space between the square stack repeating elements 220 and the inner wall of the circular cylinder 230. Other manifolding schemes are also possible.

[0060] The electrolyte 100 is preferably between 50 and 400 micrometer thick, such as 100-200 micrometer thick. Systems with thinner and thicker electrolytes are also possible. The fuel electrode 110 is preferably 20 to 50 micrometer thick, such as 30-40 micrometer thick, while the preferred thickness for the oxygen electrode 120 is between 30 and 80 micrometer, such as 45-65 micrometer thick. Other electrode thicknesses are possible. The interconnect 210 is preferably 1 to 5 mm thick, such as 2-4 mm thick. Preferred operating voltages during discharge are 0.6V to 1.0V per cell. Preferred operating voltages during charging are 1.0 to 2.1V per cell. Different voltages may be used in operation. Preferred power densities during discharge range between 100 and 1000 mW per square centimeter, such as 100-300 mW per square centimeter of electroded area. Preferred current densities during charging range between 100 and 2000 mA per square centimeter, such as 500-1500 mA per square centimeter electroded area. Larger and smaller values for power density and current density are possible. The preferred active area for each cell within a stack ranges between 9 and 500 square centimeter. The preferred dimension for the cell stack elements shown in Figure 7 is a side length between 3 and 25 cm, such as 7-15 cm. The preferred number of cells within a stack ranges from 5 cells to 200 cells, such as 50-100 cells. Larger and smaller cells as well as more and fewer cells per stack are possible.

[0061] Figures 9 to 12 illustrate a preferred SORFC system in which the fuel and the oxidized fuel are stored and regenerated. It is possible to also store and regenerate the oxidizer. However, one of the major advantages of

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SORFC is the ability to operate for an unlimited number of cycles without oxidizer storage.

[0062] The SORFC energy storage system in discharge or electricity generation mode is illustrated in Figure 9. Fuel is stored in the fuel storage vessel or tank 250. In one preferred embodiment the fuel is hydrogen which is stored as compressed gas. Other preferred storage options for hydrogen fuel include, but are not limited to cryogenic storage, metal hydrides, carbon adsorption (graphite, nanotube, or activated), sodium borohydride, and glass microspheres. Hydrocarbon fuel maybe used instead. The fuel tank SORFC connecting line 280 delivers fuel to the SORFC system 240. Oxidizer is provided from ambient through oxidizer inlet line 300 to the SORFC system 240. In the SORFC system 240, fuel is oxidized with the oxidizer and electrical energy and heat are generated. The oxidized fuel is delivered to the oxidized fuel storage tank 260 through the oxidized fuel tank SORFC system connecting line 290. In one preferred aspect, the oxidized fuel is water, and the water is stored in its liquid, solid, or partly frozen state. The depleted oxidizer is vented to ambient through the oxidizer outlet line 310.

[0063] Figure 10 illustrates the SORFC energy storage system in charge or electrolyzer mode. Stored oxidized fuel is provided from the oxidized fuel storage tank 260 to the SORFC system 240 via the oxidized fuel tank SORFC system connecting line 290. In the SORFC system 240, oxidized fuel is electrolyzed to fuel and oxidizer. The fuel generated is transported to the fuel storage tank 250 through the fuel tank SORFC system connecting line 280. The oxidizer generated in the SORFC system 240 is vented back to ambient through the oxidizer outlet line 310. Optionally, fresh oxidizer (i.e., air) can be provided to the SORFC system 240 during the charge mode through the oxidizer inlet line 300. This optional inlet stream can for example serve as the thermal control of the SORFC system.

[0064] Figure 11 illustrates one preferred layout of the SORFC energy storage system, which includes fuel and oxidizer flow control. Figure 11 illustrates this

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system in discharge mode. Fuel from the fuel storage tank 250 is provided to the SORFC input selector valve 470 through the fuel tank delivery line 520, the fluids junction 500, the fuel compressor bypass line 530, the fuel compressor bypass valve and regulator 460, the fuel compressor bypass line 531 the fluids junctions 501, and the fuel delivery line 540. An additional stream of fuel from the water/hydrogen separator and pump 410 is also delivered to the SORFC input selector valve 470 through the separator fuel outlet line 550, the fluids junction 501, and the fuel delivery line 540..

[0085] The fuel is transported from the SORFC input selector valve 470 to the SORFC 400 via the SORFC fuel side input lines 590 and 591. The fuel can be preheated in the optional fuel heat exchanger 450. In the SORFC 400, the fuel is reacted with oxidizer and generates electrical energy and heat. In a preferred layout, the fuel is only partially oxidized, and the partially oxidized fuel (i.e., hydrogen and water) is transported to the separator and pump 410 via the SORFC fuel side outlet lines 600 and 601. Preferably, the optional fuel heat exchanger 450 extracts heat from the partially oxidized fuel. The heat extracted from the partially oxidized fuel is used to heat the fuel inflow to the SORFC 400.

[0086] In the separator and pump 410 oxidized fuel (i.e., water) and fuel (i.e., hydrogen) are separated. This separator and pump 410 can preferably be a centrifugal device that both separates and adds energy to (i.e. pressurizes) the liquid and the gaseous components. The fuel is pressurized and returned to the SORFC input selector valve 470 through the separator fuel outlet line 550, the fluids junction 501, and the fuel delivery line 540, as described previously. The oxidized fuel (i.e., water) is transported from the separator and pump 410 to the oxidized fuel tank 260, via the separator oxidized fuel outlet line 560, the fluids junction 502, the oxidized fuel tank line 571, the oxidized fuel storage valve and regulator 480, and the oxidized fuel tank line 570. The separator and pump 410 delivers the oxidized fuel at a pressure suitable for storage in tank 260. In one preferred embodiment the fuel storage tank 250 and the oxidized fuel storage tank 260 are combined in one vessel.

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For the preferred option of hydrogen fuel and water as the oxidized fuel, fuel and oxidized fuel can be easily separated due to their different phases (gas vs. liquid). The gaseous fuel can provide pressurization for the liquid oxidized fuel and thereby facilitate delivery of the oxidized fuel during charge mode.

[0067] Oxidizer, such as air, needed for the oxidation of the fuel is provided to the SORFC 400 through the SORFC oxidizer side inlet lines 620, 621, 622, and 623, and the oxidizer input valve 490. The oxidizer is driven into the SORFC 400 by the oxidizer blower 430. The oxidizer can be preheated in the optional oxidizer heat exchanger 440. The depleted oxidizer is vented through the SORFC oxidizer side outlet lines 610 and 611. Lines 610 and 611 preferably pass through the optional oxidizer heat exchanger 440 to extract heat from the depleted oxidizer outlet stream and thereby preheat the oxidizer inflow. Alternatively, the incoming fuel may be preheated by the depleted oxidizer stream and/or the incoming oxidizer may be preheated by the oxidized fuel stream, if the location of lines 600/601 and/or 610/611 is reversed with respect to heat exchangers 440, 450.

[0068] The valve and regulator 460 is open in the discharge mode, while the fuel compressor valve 455 is closed. Valve 470 is a three way valve, which is switched to allow fuel flow between lines 540 and 590, while preventing oxidized fuel flow from line 630 to line 590.

[0069] Figure 12 illustrates how the system shown in Figure 11 operates in the charge mode. Oxidized fuel (i.e., water) is delivered to the SORFC input selector valve 470 from the oxidized fuel storage tank 260 via the oxidized fuel tank line 570, the open oxidized fuel storage valve and regulator 480, the oxidized fuel tank line 571, the fluids junction 502, and the oxidized fuel delivery line 630. Additional oxidized fuel is provided from the separator and pump 410 to the SORFC input selector valve 470 via the separator oxidized fuel outlet line 560, the fluids junction 502, and the oxidized fuel delivery line 630. The oxidized fuel is transported from the SORFC input selector valve

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470 to the SORFC 400 through the SORFC fuel side input lines 590 and 591. The oxidized fuel can be preheated in the optional fuel heat exchanger 450.

[0070] In the SORFC 400, the oxidized fuel is electrolyzed. Partly regenerated fuel (i.e., hydrogen and water) is transported from the SORFC 400 to the separator and pump 410 through the SORFC fuel side outlet lines 600 and 601. The optional fuel heat exchanger 450 can extract heat from the partially regenerated fuel and provide pre-heat to the oxidized fuel inflow. In the separator and pump 410, the regenerated fuel (i.e., hydrogen) and oxidized fuel (i.e., water) are separated. Fuel is transported from the separator and pump 410 to the fuel tank 250 through the separator fuel outlet line 550, the fluids junction 501, the fuel compressor line 512, the optional fuel compressor valve 455, the fuel compressor line 511, the optional fuel compressor 420, the fuel compressor line 510, the fluids junction 500, and the fuel tank delivery line 520. The optional compressor 420 pressurizes the fuel for storage in the fuel storage tank 250. The optional compressor 420 is preferably an electrochemical hydrogen pump. Oxidized fuel from the separator and pump 410 is re-circulated to the SORFC input selector valve 470 via the separator oxidized fuel outlet line 560, the fluids junction 502, and the oxidized fuel delivery line 630. The separator and pump 410 brings the output oxidized fuel to a pressure suitable for recirculation.

[0071] Regenerated oxidizer is vented from the SORFC 400 to ambient via the SORFC oxidizer side outlet lines 610 and 611. The optional oxidizer heat exchanger 440 can extract heat from the regenerated oxidizer outflow. Optionally, additional oxidizer can be provided from ambient to the SORFC 400 through the SORFC oxidizer inlet line 620, the oxidizer blower 430, the SORFC oxidizer inlet line 621, the oxidizer input valve 490, the SORFC oxidizer inlet line 622, and the SORFC oxidizer inlet line 623. The optional oxidizer heat exchanger 440 can add heat to the oxidizer inflow. In one preferred embodiment the optional oxidizer inflow provides thermal control for the SORFC 400.

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[0072] The valve and regulator 460 is closed in the charge mode, while valve 455 is open. Valve 470 is a three way valve, which is switched to prevent fuel flow between lines 540 and 590, while allowing oxidized fuel flow from line 630 to line 590.

[0073] The SORFC system 240 described previously contains the SORFC 400 and controlling elements, associated electrical circuits, peripheral fluid lines, valves and heat exchangers. The fuel tank SORFC system connecting line 280 includes lines 510, 511, 512, 520 and 540. The oxidized fuel tank SORFC system connecting line includes lines 560, 570, 571, 590, 591, 600, 601, and 630. The oxidizer inlet line 300 includes lines 620, 621, 622, and 623. The oxidizer outlet line 310 includes lines 610 and 611.

[0074] The SORFC energy storage system can be sized for a wide range of power and energy storage requirement. Preferred power levels range from 1kW to 10MW, but smaller and larger systems are possible. There are virtually no limits for the amount of energy that can be stored. Appropriate tank sizing can store energy from a few Whr (Watt hours) to GWhr (Gigawatt hours). The SORFC energy storage system is especially advantageous at large energy levels, where large energy storage densities can be realized. Energy storage densities in excess of 450 Whr/kg can be realized. Energy storage efficiencies (energy available in discharge divided by energy needed to charge) on the order of 0.5 can be realized.

[0075] The foregoing description of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the invention. The drawings are not necessarily to scale and illustrate the device in schematic block format. The drawings and description of the preferred embodiments were chosen in order to explain the principles of the invention and its practical application, and are not meant to be limiting on

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the scope of the claims. It is intended that the scope of the invention be defined by the claims appended hereto, and their equivalents.

[0076] Parts list:

- 100 electrolyte
- 110 fuel electrode
- 120 oxygen electrode
- 122 fuel side electrical connection
- 126 oxygen side electrical connection
- 130 fuel inflow
- 140 oxidized fuel outflow
- 150 oxidizer inflow
- 160 depleted oxidizer outflow
- 170 oxidized fuel inflow
- 180 regenerated fuel outflow
- 190 optional oxygen side inflow
- 200 regenerated oxidizer outflow
- 210 interconnect
- 220 repeating elements
- 230 gas manifold
- 240 SORFC system
- 250 fuel storage tank
- 260 oxidized fuel storage tank
- 280 fuel tank SORFC system connecting line
- 290 oxidized fuel tank SORFC system connecting line
- 300 oxidizer inlet line
- 310 oxidizer outlet line
- 400 Solid Oxide Regenerative Fuel Cell (SORFC)
- 410 fuel/oxidized fuel separator and pump
- 420 fuel compressor
- 430 oxidizer blower
- 440 oxidizer heat exchanger
- 450 fuel heat exchanger

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455 fuel compressor valve  
460 fuel compressor bypass valve and regulator  
470 SORFC input selector valve  
480 oxidized fuel storage valve and regulator  
490 oxidizer input valve  
500 fluids junction  
501 fluids junction  
502 fluids junction  
510 fuel compressor line  
511 fuel compressor line  
512 fuel compressor line  
520 fuel tank delivery line  
530 fuel compressor bypass line  
531 fuel compressor bypass line  
540 fuel delivery line  
550 separator fuel outlet line  
560 separator oxidized fuel outlet line  
570 oxidized fuel tank line  
571 oxidized fuel tank line  
590 SORFC fuel side input line  
591 SORFC fuel side input line  
600 SORFC fuel side outlet line  
601 SORFC fuel side outlet line  
610 SORFC oxidizer side outlet line  
611 SORFC oxidizer side outlet line  
620 SORFC oxidizer inlet line  
621 SORFC oxidizer inlet line  
622 SORFC oxidizer inlet line  
623 SORFC oxidizer inlet line  
700 solar array  
710 electrical cable  
720 electrical cable

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- 730 electrical cable
- 740 motor propeller
- 750 SOFC
- 760 electrical cable
- 800 heat transfer loop
- 810 payload or equipment

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We claim:

1. A solid oxide fuel cell adapted to power an airborne vehicle.
2. The fuel cell of claim 1, wherein the solid oxide fuel cell comprises a solid oxide regenerative fuel cell (SORFC).
3. The fuel cell of claim 2, wherein:
  - the SORFC is adapted to power an unmanned, solar powered airplane in absence of sunlight; and
  - the SORFC is adapted to regenerate fuel using electricity generated from sunlight.
4. The fuel cell of claim 1, wherein the solid oxide fuel cell comprises a non-regenerative solid oxide fuel cell (SOFC).
5. The fuel cell of claim 2, wherein the SOFC is adapted to power an unmanned, electrically powered airplane.
6. The fuel cell of claim 1, wherein the fuel cell is also adapted to provide heat to payload or equipment of the airborne vehicle.
7. An electrically powered airplane, comprising:
  - an airplane body;
  - a solid oxide fuel cell adapted to power the airplane; and
  - a fuel storage vessel adapted to provide fuel to the solid oxide fuel cell.
8. The airplane of claim 7, wherein the airplane comprises an unmanned, propeller driven high altitude airplane.
9. The airplane of claim 8, wherein:
  - the airplane comprises a solar powered airplane containing a solar cell array;
  - the solid oxide fuel cell comprises a solid oxide regenerative fuel cell (SORFC);
  - the SORFC is adapted to power the airplane in absence of sunlight; and
  - the SORFC is adapted to regenerate fuel using electricity generated from sunlight by the solar cell array.

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10. The airplane of claim 8, wherein the solid oxide fuel cell comprises a non-regenerative solid oxide fuel cell (SOFC).
11. The airplane of claim 8, further comprising an oxidized fuel storage vessel adapted to store oxidized fuel output by the fuel cell.
12. The airplane of claim 11, wherein:  
the fuel storage vessel is adapted to store hydrogen; and  
the oxidized fuel storage vessel is adapted to store water.
13. The airplane of claim 7, wherein the fuel storage vessel is adapted to store both hydrogen fuel and water oxidized fuel.
14. The airplane of claim 12, further comprising:  
an air inlet adapted to provide air to the fuel cell; and  
an air outlet adapted to vent air from the fuel cell.
15. The airplane of claim 7, further comprising a heat transfer loop adapted to transfer heat from the fuel cell to payload or equipment located remotely in the airplane body.
16. The airplane of claim 7, further comprising a motor propeller system which is powered by the fuel cell.
17. The airplane of claim 7, further comprising an oxidized fuel separation and fuel pump system adapted to separate partially oxidized fuel output by the fuel cell into fuel and oxidized fuel, to pump fuel into the fuel cell or the fuel storage vessel, and to pump oxidized fuel into an oxidized fuel storage vessel or into the fuel cell.
18. An electrically powered airplane, comprising:  
an airplane body;  
a fuel cell adapted to power the airplane and to heat remotely located payload or equipment in the airplane body; and  
a fuel storage vessel adapted to provide fuel to the solid oxide fuel cell.
19. The airplane of claim 18, wherein:  
the fuel cell comprises a solid oxide fuel cell; and  
the airplane comprises an unmanned, propeller driven high altitude airplane.

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20. The airplane of claim 19, wherein:

the airplane comprises a solar powered airplane containing a solar cell array;

the solid oxide fuel cell comprises a solid oxide regenerative fuel cell (SORFC);

the SORFC is adapted to power the airplane in absence of sunlight; and

the SORFC is adapted to regenerate fuel using electricity generated from sunlight by the solar cell array.

21. The airplane of claim 19, wherein the solid oxide fuel cell comprises a non-regenerative solid oxide fuel cell (SOFC).

22. The airplane of claim 19, further comprising an oxidized fuel storage vessel adapted to store oxidized fuel output by the fuel cell.

23. The airplane of claim 22, wherein:

the fuel storage vessel is adapted to store hydrogen; and

the oxidized fuel storage vessel is adapted to store water.

24. The airplane of claim 22, further comprising:

an air inlet adapted to provide air to the fuel cell; and

an air outlet adapted to vent air from the fuel cell.

25. The airplane of claim 18, further comprising a heat transfer loop adapted to transfer heat from the fuel cell to payload or equipment located remotely in the airplane body.

26. A solid oxide fuel cell system, comprising:

a first means for providing oxygen ion conduction to generate a potential difference between a fuel electrode and an oxygen electrode; and

a second means for providing electric power to an airborne vehicle from the potential difference.

27. The fuel cell of claim 26, further comprising a third means for providing fuel to the first means and a fourth means for providing oxidizer to the first means.

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28. The fuel cell of claim 27, wherein the first means generates electrical energy from the fuel and the oxidizer in a discharge mode and the first means regenerates the fuel from oxidized fuel in a charge mode.
29. The fuel cell of claim 28, wherein the fuel comprises hydrogen, the oxidizer comprises oxygen or air and the oxidized fuel comprises water.
30. A method of generating power in an airborne vehicle, comprising:
  - providing a fuel and a oxidizer to a solid oxide fuel cell; and
  - providing electrical power from the fuel cell to a motor propeller system of the airborne vehicle.
31. The method of claim 30, further comprising:
  - converting sunlight into electrical energy;
  - providing the electrical energy to the solid oxide fuel cell;
  - providing oxidized fuel into the fuel cell;
  - electrolyzing the oxidized fuel in the solid oxide fuel cell into partially regenerated fuel;
  - separating fuel from oxidized fuel in the partially regenerated fuel; and
  - storing the fuel and the oxidized fuel.
32. The method of claim 30, further comprising providing heat to remotely located payload or equipment from the fuel cell.
33. An SORFC power generation system, comprising:
  - at least one SORFC cell;
  - a fuel storage vessel;
  - an oxidizer inlet;
  - an oxidized fuel storage vessel; and
  - a first means for:
    - (a) separating partially regenerated fuel provided from the at least one SORFC cell into regenerated fuel and oxidized fuel, for directing the regenerated fuel into the fuel storage vessel and for directing oxidized fuel back into the at least one SORFC cell; and
    - (b) separating partially oxidized fuel provided from the at least one SORFC cell into fuel and oxidized fuel, for directing the fuel back into the at

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least one SORFC, and for directing oxidized fuel into the oxidized fuel storage vessel.

34. The system of claim 33, further comprising a compressor adapted to compress and provide the regenerated fuel into the fuel storage vessel.

35. The system of claim 33, further comprising at least one heat exchanger adapted to preheat fuel incoming into the at least one SORFC cell using output of the at least one SORFC cell.

36. The system of claim 33, wherein the system is located in an airborne vehicle.

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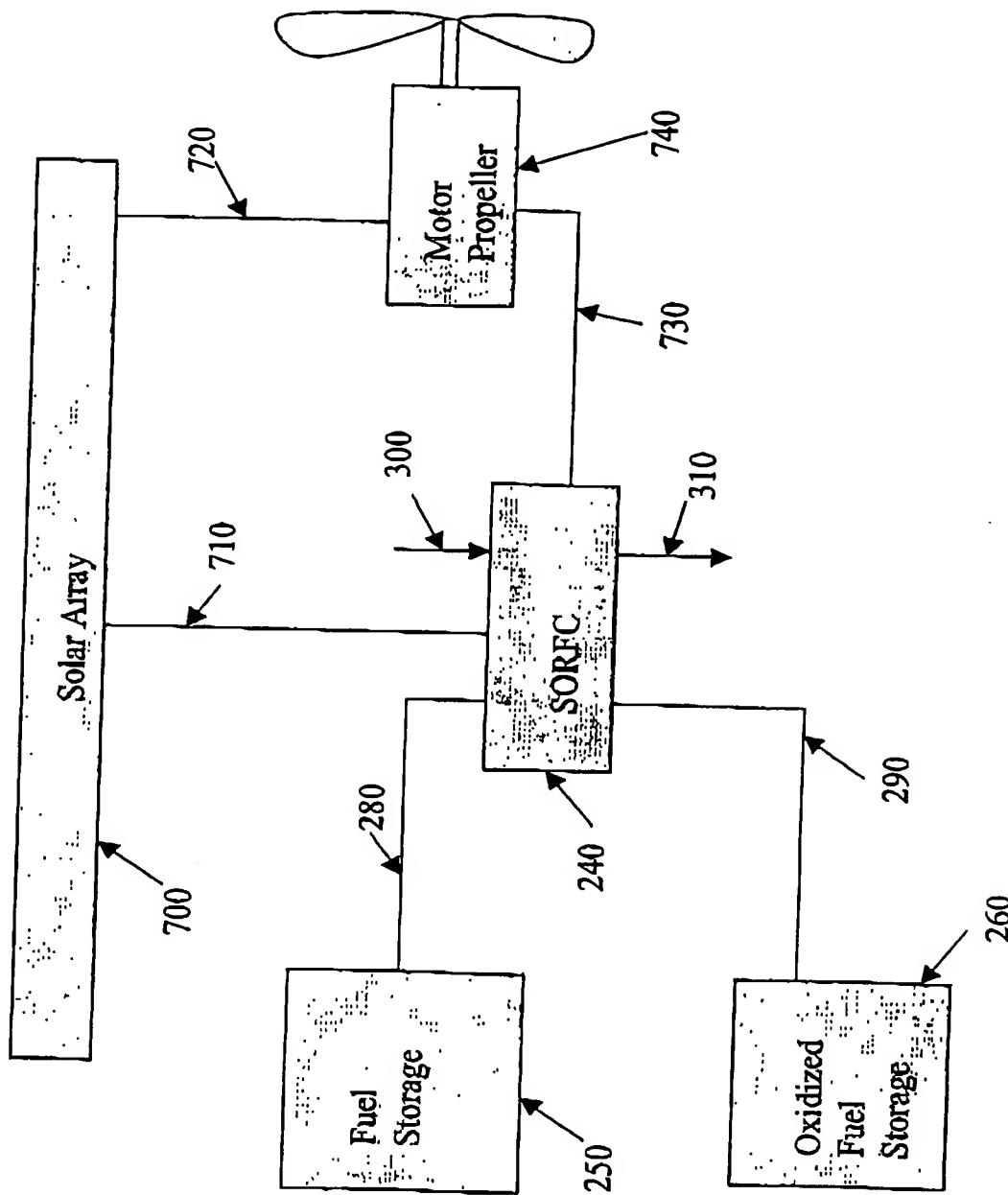


Figure 1

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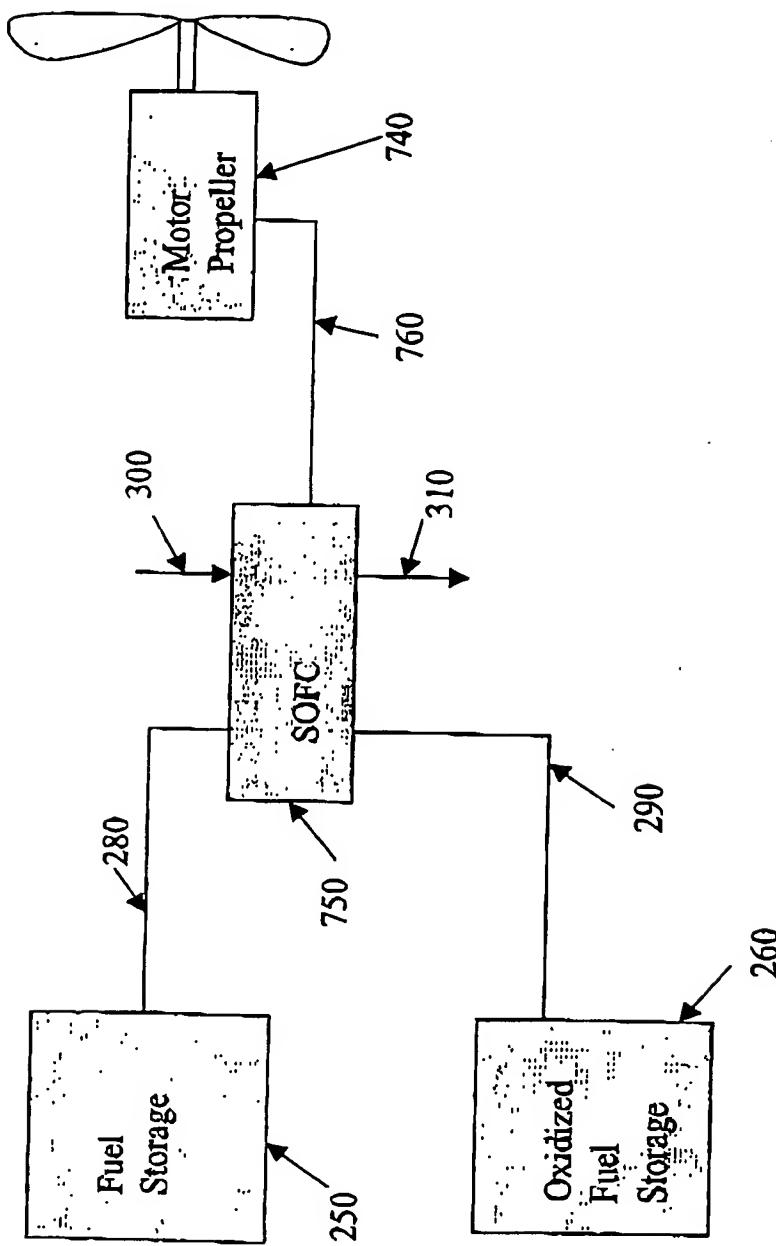


Figure 2

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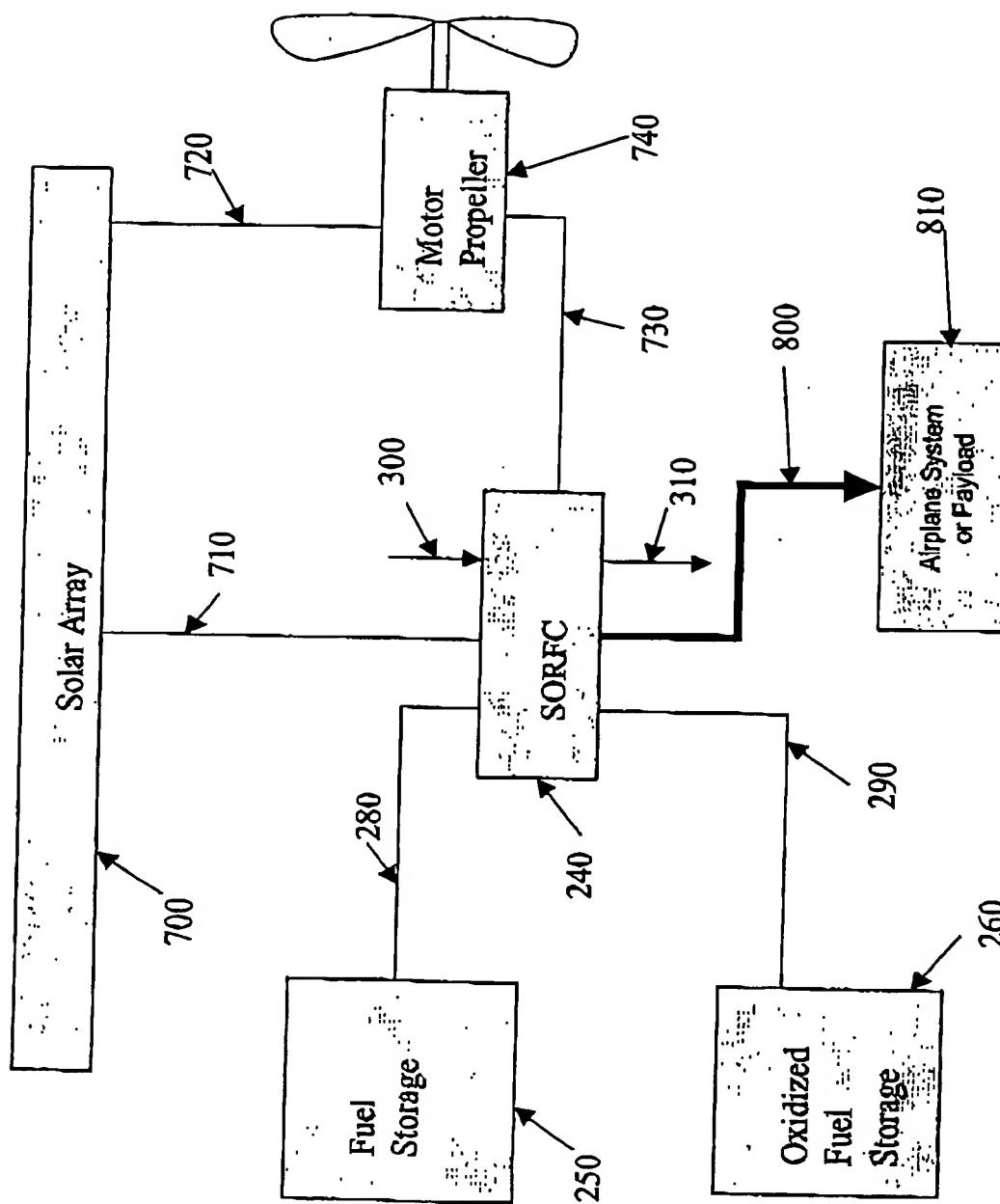


Figure 3

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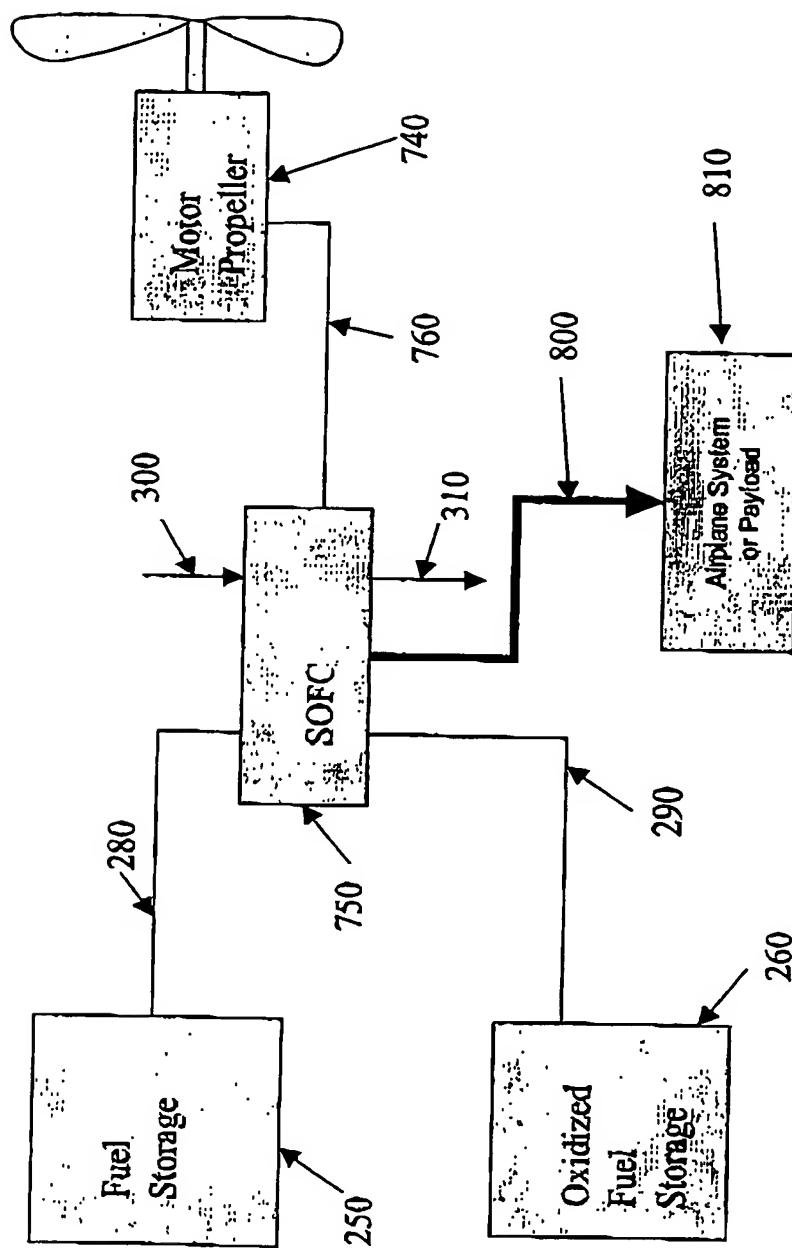


Figure 4

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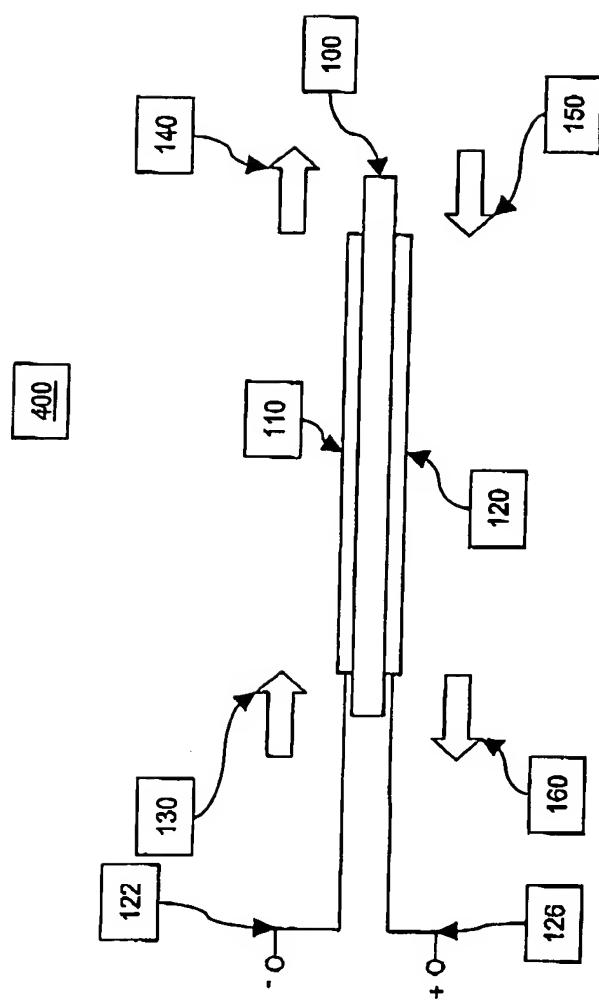


Figure 5

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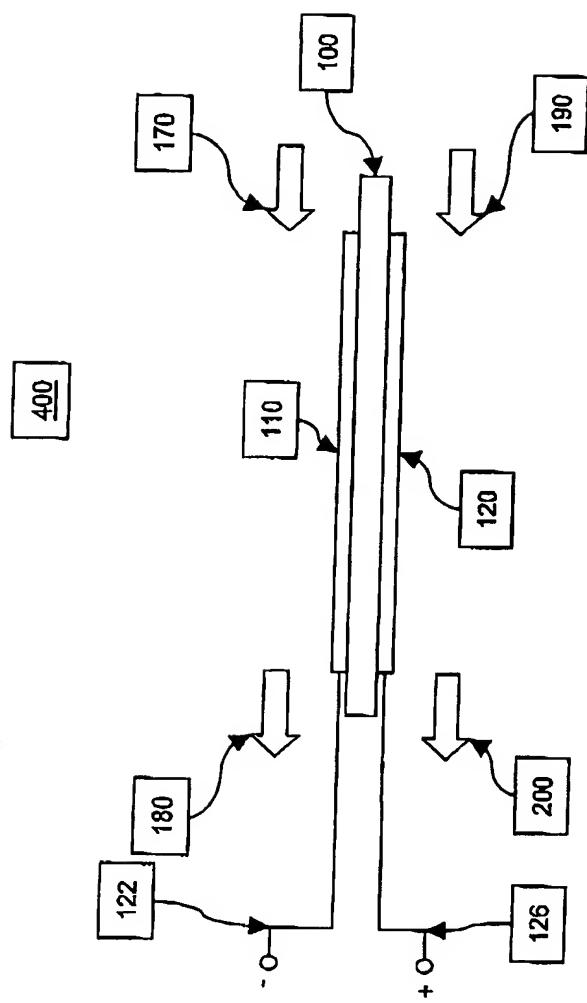


Figure 6

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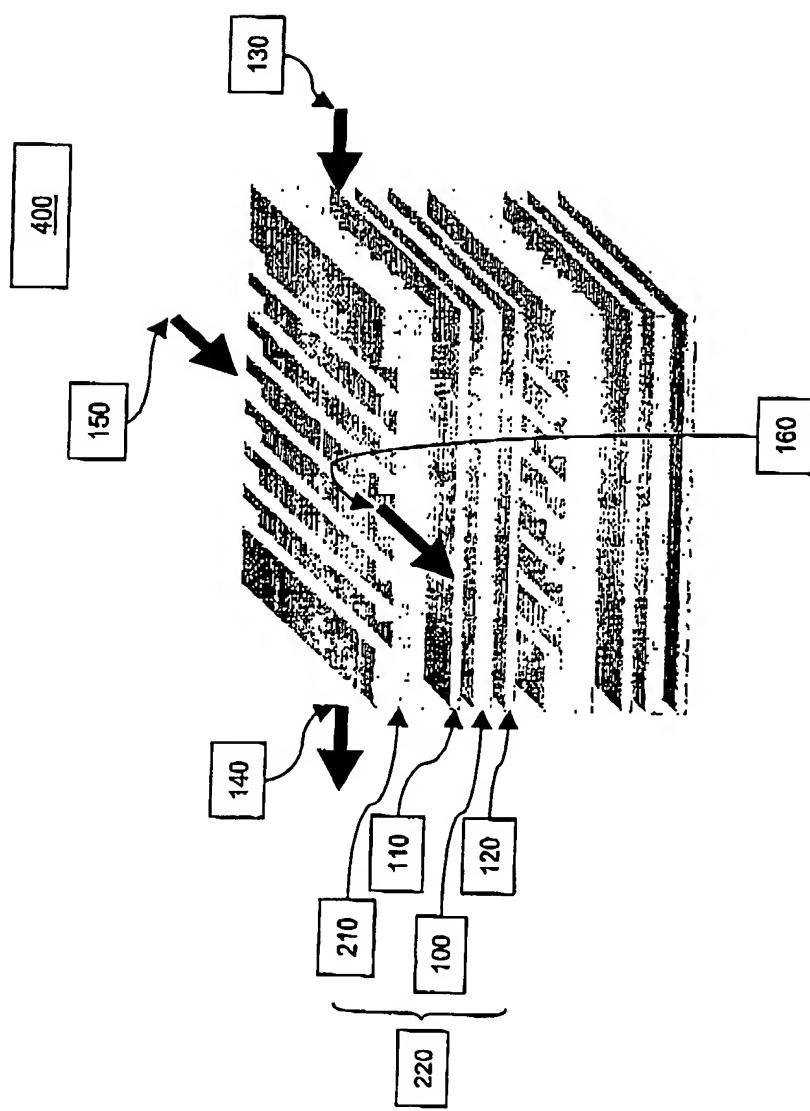


Figure 7

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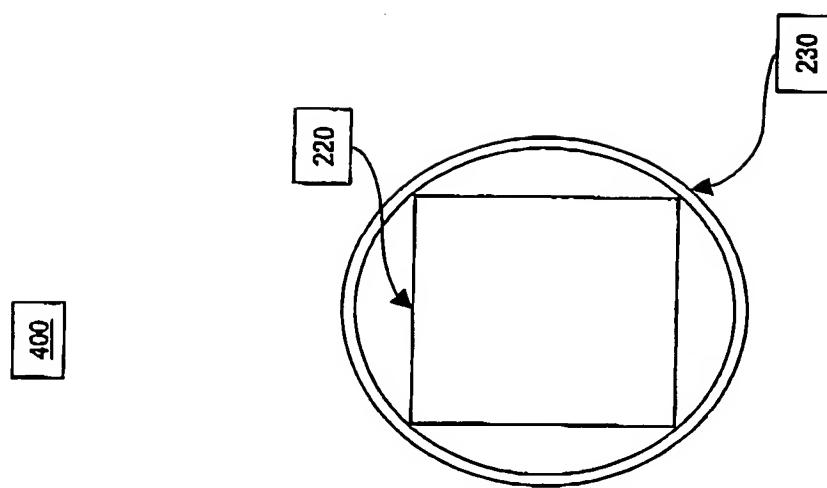


Figure 8

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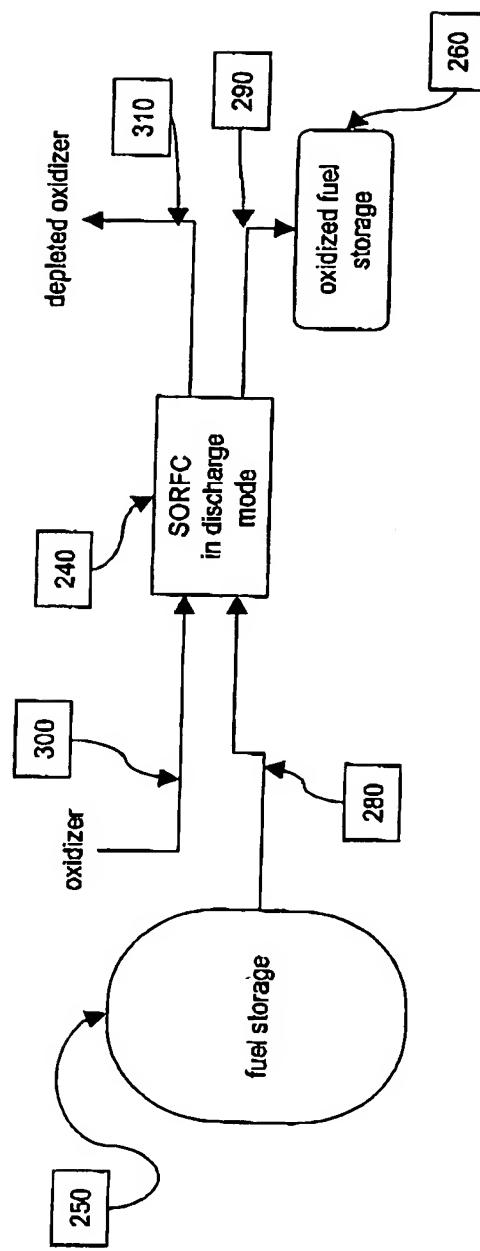


Figure 9

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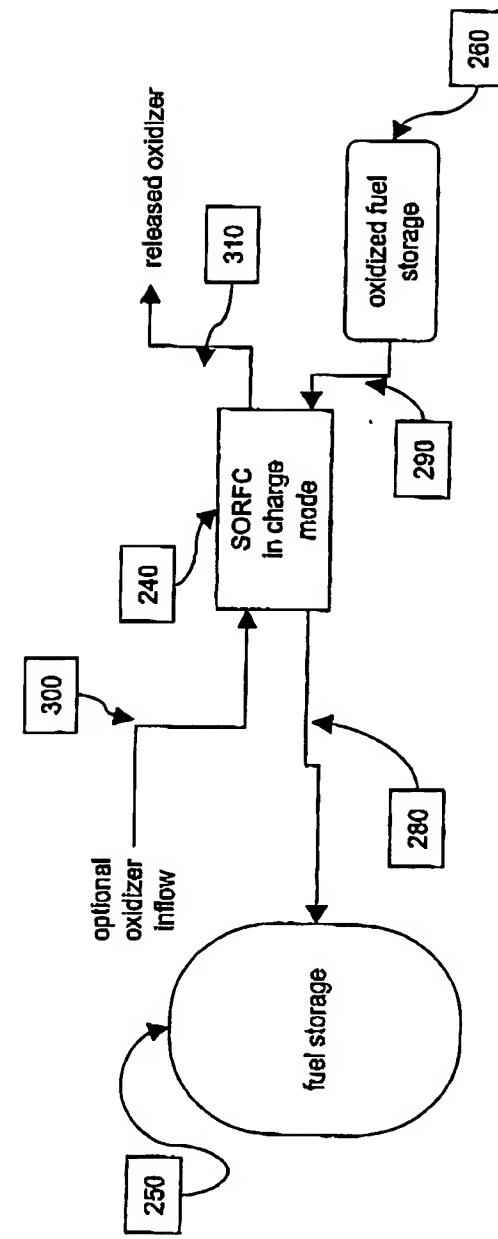


Figure 10

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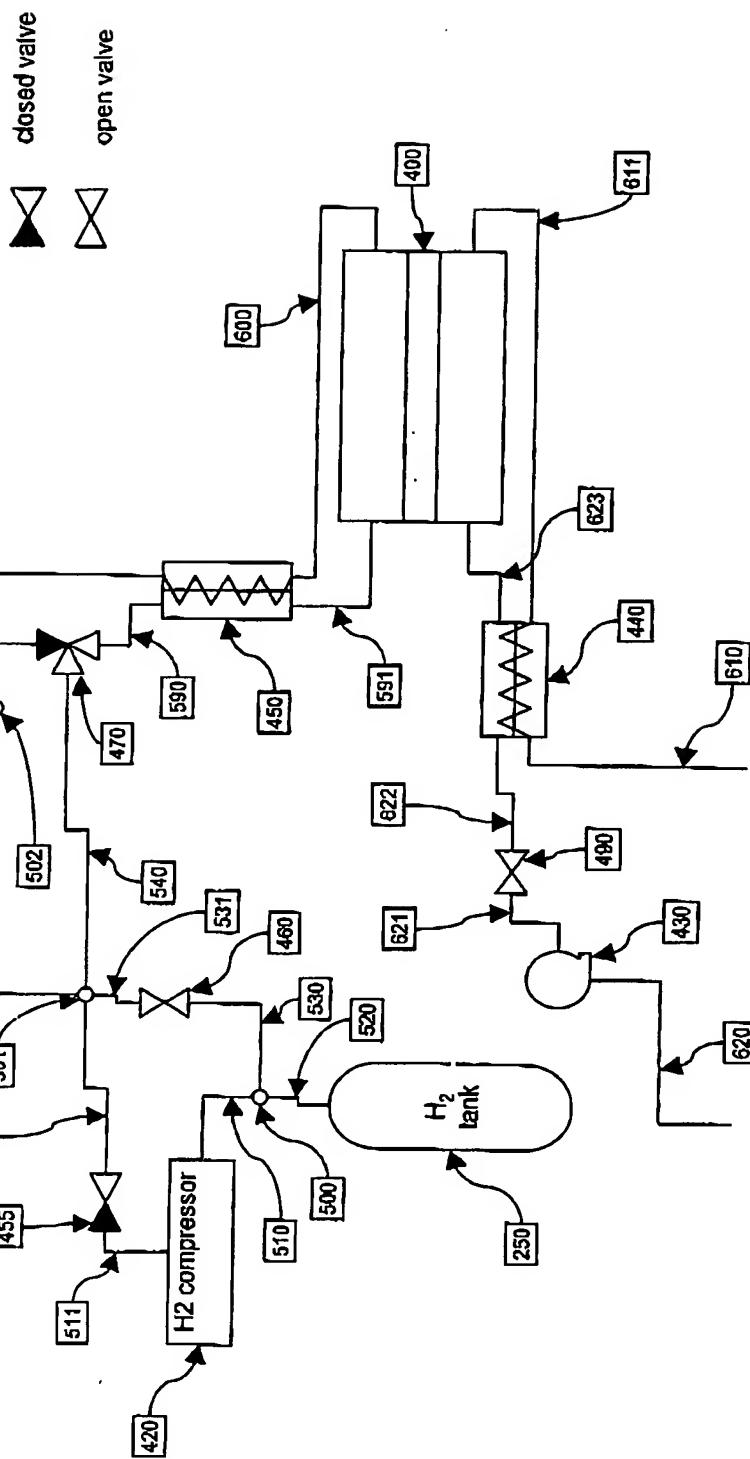


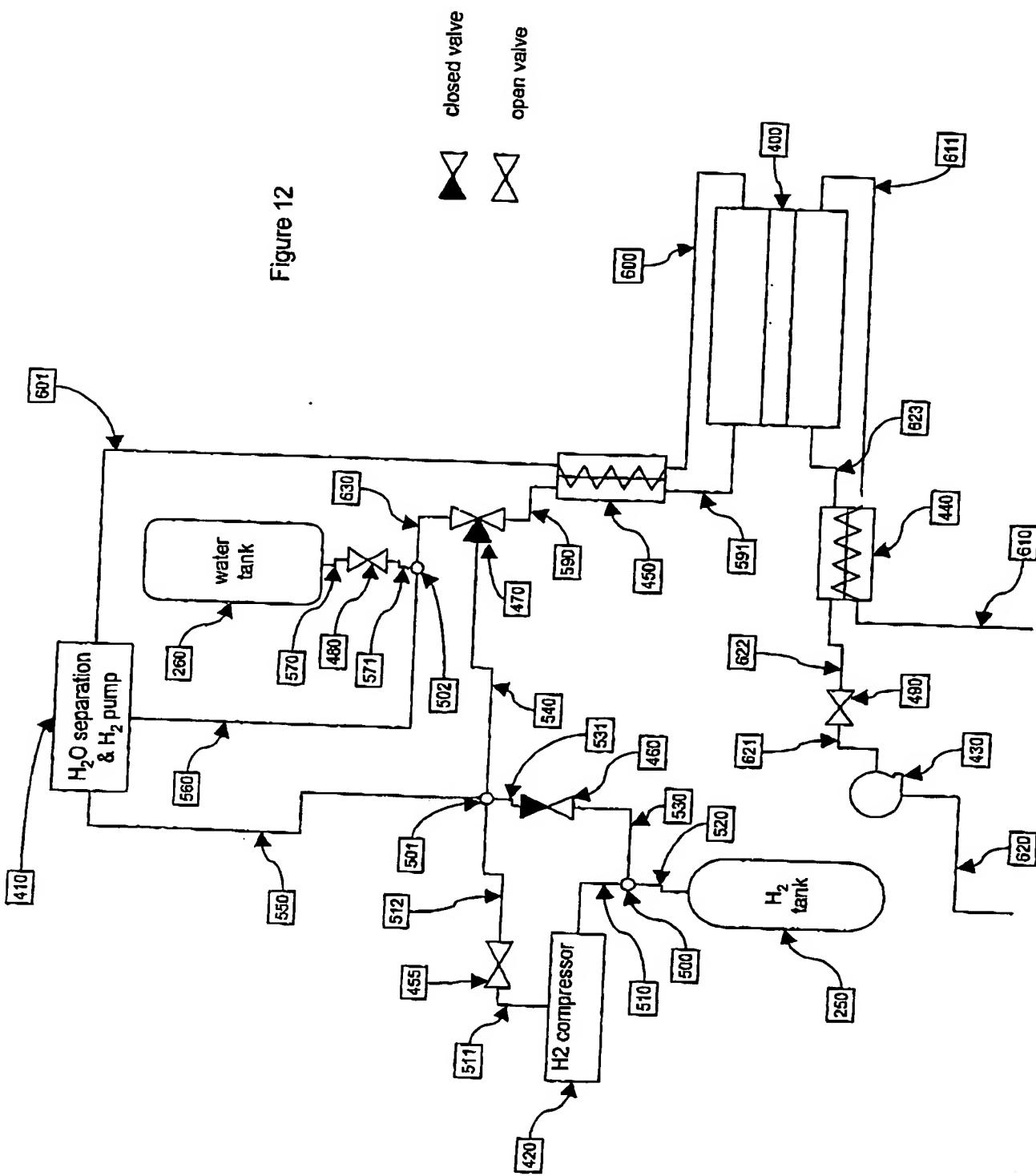
Figure 11

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Figure 12



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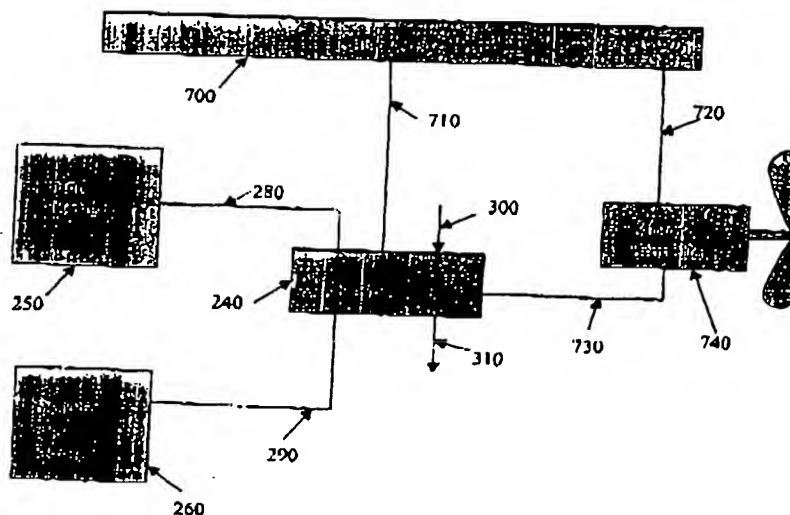
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(54) Title: SOLID OXIDE REGENERATIVE FUEL CELL FOR AIRPLANE POWER GENERATION AND STORAGE



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(57) Abstract: A Solid Oxide Regenerative Fuel Cell (SORFC) (240) or a Solid Oxide Fuel Cell (SOFC) (750) is incorporated into an electrically powered airplane to provide either regenerative or primary electrical energy. The SORFC (240), the SOFC (750), or any other suitable fuel cell within an airplane may also be used to heat payload or equipment (810) within the airplane. The SORFC (240) is not only capable of generating electrical energy from fuel and a suitable oxidizer, but can also generate fuel through electrolysis of oxidized fuel. Thus, the SORFC (240) system powering an airplane can obtain oxygen oxidant reactant from the air and avoid the complexity, weight, volume, and cost associated with oxygen storage.

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*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

## INTERNATIONAL SEARCH REPORT

International application No.

US03/19151

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Minimum documentation searched (classification system followed by classification symbols)

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields  
SEARCHEDElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
NONE

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,106,035 A (LANGFORD, II) 21 APRIL 1992 (21/04/1992) SEE FIGURE 2	NONE
Y	US 5,810,284 A (HIBBS ET AL) 22 SEPTEMBER 1998 (22/09/1998) SEE FIGURE 11	1-5,7-14,16-24,26-31,33-36
A,E	US 6,550,717 B2 (MACCREADY ET AL) 22 APRIL 2003 (22/04/2003) SEE FIGURE 6	NONE
X,E — Y,E	US 6,568,633 B2 (DUNN) 27 MAY 2003 (27/05/2003) SEE FIGURE 5	1-2,7-8,10-14,16-19,26-30,33,34,36 — 1-36

Further documents are listed in the continuation of Box C.  See patent family annex.

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International application No.  
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## C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,E	US 2002/0114985 A1 (SHKOLNIK ET AL) 22 AUGUST 2002 (22/08/2002) SEE FIGURE 9	6,15,25,82,85

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Pour le titre du livre  
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HOIM 8/28C2

HOIM 8/06B6

HOIM 14/00

HOIM 8/54-H

HOIM 8/54-C2

## REGENERATIVE FUEL CELL FOR ENERGY STORAGE IN PV SYSTEMS

p. 538 - 541

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### ABSTRACT

Regenerative fuel cells (RFCs) are of great interest for storing energy in various space applications. In general the systems are based on the electrolysis of water, the storage of hydrogen and oxygen, and the following recombination to water in a fuel cell. Three basic cell concepts have to be distinguished - dedicated, integrated, reversible. There are important differences between these concepts and additionally the performance of the RFCs is influenced by the type of electrochemical cell - alkaline, membrane. Solar systems in stand-alone applications suffer from the lack of availability of reasonable seasonal energy storage. RFCs are a very promising option for terrestrial photovoltaic installations and the feasibility will be demonstrated in the energetically self-sufficient solar house, which will be built in the near future.

### INTRODUCTION

The work on regenerative hydrogen-oxygen fuel cells has been directed towards their use in space applications during the past 30 years / 1-3/. The regenerative fuel cell (RFC) constitutes a storage system for electrical energy, and can be operated in the same modes as secondary batteries. During the discharge mode the fuel cell converts the stored gases - hydrogen and oxygen - in an electrochemical reaction to electricity and water. The system is recharged by feeding electricity to an electrolysis unit, which dissociates the product water and forms hydrogen and oxygen. The gases are stored in cylinders under pressure.

There are various RFCs under development differing in the degree of integration of the components and in the technologies of the selected electrochemical devices.

To meet the future power demands for mid- to high-orbit satellites or space stations, research is going on in the areas of solar power generation, energy storage and power management /4/. Main emphasis is directed toward achieving the lowest weight of the overall power system, which depends strongly on the characteristics of the energy storage system. Considering these aspects RFCs are one of the most promising candidates.

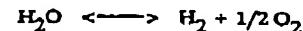
Notwithstanding the space applications, RFCs offer attractive advantages that can be very useful for terrestrial photovoltaic systems. However the requirements differ very much, because instead of weight cost is the most important criterion.

As a result of our work on energy storage for decentralized photovoltaic systems /5/ it turned out that there is no reasonable device available for long term energy storage. PV stand-alone systems with power demands in the range of kW have to be installed in combination with wind power or diesel generators. The lack of seasonal energy storage is overcome by these measures, nevertheless the complexity of the systems increases, resulting in reduced reliability and higher cost.

Within the framework of our actual work on the energetically self-sufficient solar house /6/ the development of a novel energy storage system was initiated with the aim to demonstrate the suitability of RFCs in conventional solar applications.

### REGENERATIVE FUEL CELL TECHNOLOGIES

RPCs consist in general of electrolyser, gas cylinders, liquid storage tanks, and fuel cell. The most common systems are based on the reversible reaction:



Systems using hydrogen - chlorine /7/ or hydrogen - bromine /8/ are favourable with respect to the electrochemical reaction kinetics, but cause severe safety problems. The comparison and assessment of the three hydrogen - halogen concepts give preference to the hydrogen - oxygen RFC and thus the main research efforts are focused on that system.

Looking in detail at the hydrogen-oxygen RFC the flexibility and variability of the system is evident. Many variations concerning the electrolyser, the fuel cell and all the other system components are possible.

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In the past, three arrangements of the electrochemical devices were under consideration, termed dedicated, integrated and reversible design.

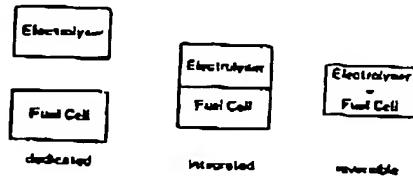


Fig. 1: RFC system design

In Fig. 1 the schemes of the three concepts are illustrated. The dedicated design is based on separate fuel cell and electrolyser. Each unit is able to operate independently and is provided with all the necessary auxiliary equipment.

The integrated design achieves a higher degree of compactness by combining single fuel cells and electrolysis cells in one common casting. This configuration requires careful design of the associated equipment to guarantee the proper function during the two modes of operation.

The most advanced concept with respect to the electrochemical performance constitutes the reversible design. Each individual electrochemical cell is able to work as well in the electrolysis as in the fuel cell mode. The capability of the cells to operate in both modes simplifies the configuration of the overall system to a great extent. These principal advantages make it possible to develop very reliable and cost effective RFCs in future.

The type of electrochemical cells selected for electrolysis or fuel cell operation determines the system configuration and the detail engineering. Up to now most of the research was concentrated on alkaline electrolyzers and fuel cells. In the 1960s work was commenced on reversible /1/ and dedicated /9/ systems. The low performance of reversible cells due to the difficulties in the oxygen electrode led to intensified research on the integrated design. New techniques were developed, such as the "valve electrode" /2/, which combines two separate electrodes for gas evolution and reduction respectively in one single structure, or the concept of alternately stacking electrolysis cells and fuel cells inside a pressure vessel to form an integrated system /10/.

In parallel to the early work on alkaline cells research on cells with solid polymer electrolytes (SPFC) was started /11/, but the cells failed because of the instability of the membranes. Today, due to the availability of chemically stable ion exchange membranes, there is renewed interest in the SPFC technology, especially for the application in space /12, 13/. The efforts are mainly focused on the dedicated design, because of the problems associated with the oxygen electrode. Recently a novel concept to overcome the poor performance of the oxygen electrode was developed /14, 15/.

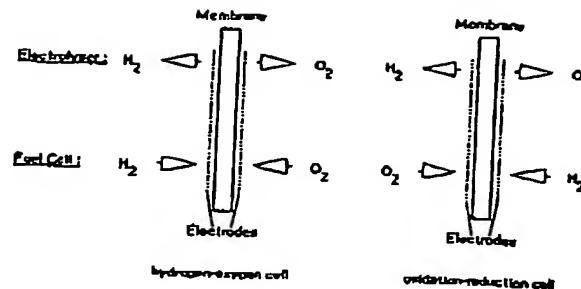


Fig. 2: Reversible SPFC.

In Fig. 2 two drafts of principal arrangements of the reversible SPFC are shown. The first illustrates the conventional hydrogen-oxygen cell with reversible hydrogen electrodes and reversible oxygen electrodes. In the second sketch the arrangement is nearly the same, but simultaneous to the change of the operational mode from electrolysis to fuel cell the gases in the electrode compartments are reversed. These measures ensure very favourable electrochemical performance of the electrodes, for the one operates as oxidation electrode and the other as reduction electrode under all operational conditions. The selection of appropriate catalysts is facilitated and besides platinum for the reduction electrode the very active iridium is the proper choice for the oxidation electrode. The main advantages of the concept are higher efficiencies, more flexibility in the selection of cell materials, and improved durability of the catalysts. The need for additional equipment to keep the gas switching under control may be regarded as drawback.

#### RFC FOR THE ENERGETICALLY SELF-SUFFICIENT SOLAR HOUSE

In our institute, we are presently very active in developing and performing the detail engineering of an energetically self-sufficient solar house /6/. The project is ambitious, because we intend to demonstrate that it is possible to meet all the energy demands of the residence entirely by solar energy. The house that will be constructed this year will be equipped with various solar thermal systems and photovoltaics, but will not be connected to the utility network or consume any type of fossil fuels. Solar thermal systems will deliver the heat required for space heating and warm water. The photovoltaic generator will produce electricity for the electric devices and for cooking. The discontinuous supply of solar energy makes it necessary to install an adequate energy storage system to buffer the daily, weekly, or yearly fluctuations. In the beginning of our work various concepts for seasonal storage were compared /16/ and as a result of the system calculations a modified RFC system was selected. The hybrid energy storage system is adapted to the special requirements called for, such as low power, high capacity, and long term storage.

### Seasonal storage system

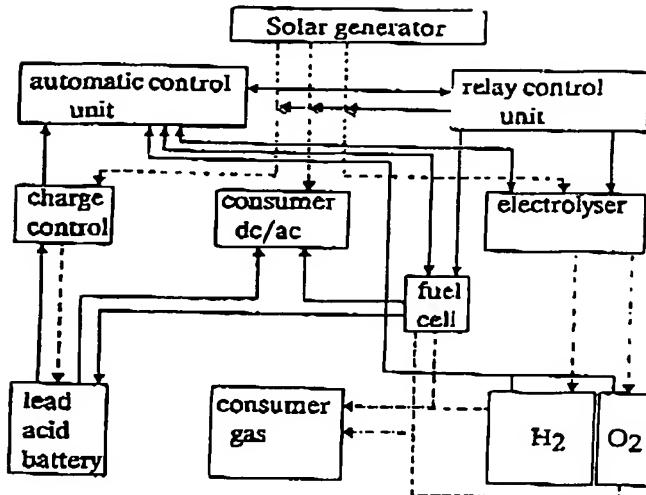


Fig. 3

Fig. 3 shows the flow-chart of the seasonal storage system. The flow of electricity from the solar generator is supervised by the control system, which switches the current with first priority to the actual consumer, secondly to the battery, and thirdly to the hydrogen-oxygen RFC. Following this sequence of priorities the highest conversion efficiencies are attained. The RFC is composed of electrolyser, pressure cylinders (30 bar) for hydrogen and oxygen, fuel cell, and additional gas consumers, e.g. catalytic cooker or furnace /17/.

On the basis of very detailed simulations of the performance of the entire house the size and specific data of the seasonal storage system have been finally defined.

#### Energy demand:

- electric	1.800 kWh/a
- high temperature heat	1.250 kWh/a
<b>Hybrid storage:</b>	
- lead-acid battery	20 kWb
- electrolyser	0.9 kW
- fuel cell	0.6 kW
- catalytic cooker	2.0 kW
- gas storage	1.350 kWh ( $H_2$ 15 m <sup>3</sup> , $O_2$ 7.5 m <sup>3</sup> )

#### SELECTION OF THE RFC COMPONENTS

The development of the dedicated RFC was started with the intention to select and buy the single components from commercial suppliers. We have been successful in purchasing lead-acid batteries, alkaline electrolyser, alkaline fuel cell, and gas cylinders.

During testing procedures technical problems appeared concerning the operation of electrolyser and fuel cell, which are due to electrolyte creepage, gas management, and high energy consumption of the associated equipment. Our experience shows that it is extremely difficult to handle the aggressive KOH in such small devices and to overcome the safety risks caused by the hot electrolyte (80 °C) under pressures of up to 30 bar. Therefore, the applicability of electrolyser and fuel cell with solid polymer membrane electrolyte has been investigated, and the study showed such attractive advantages that the decision was made to strive for the use of membrane systems. Failing in the attempt to purchase electrochemical membrane cells, research was initiated three years ago. At present tests are carried out on a membrane type pressure electrolyser designed and fabricated in our institute. The basic design of the electrolyser system is very similar to that of the alkaline type, but beside the use of bipolar membrane cells the design was optimized to reduce the power consumption of the auxiliary equipment. The decrement from 60 W to 15 W was achieved by exchanging the electrically actuated valves by pneumatically operated devices.

Both pressure electrolyzers, alkaline and membrane electrolyte, are undergoing endurance tests and at the end of this year one of them will be selected for installation into the house.

In the beginning, our work on fuel cells was concentrated on the development of system technology integrating one commercially available alkaline cell stack. Main activities were related to the automatic control system, the gas supply, and the electrolyte management. Unfortunately it was not possible to achieve satisfying operation of the fuel cell, because of electrolyte creepage and flooding of the electrodes. Thus, that work was stopped.

Alternatively we looked for commercial prototypes and we will be supplied with two systems shortly. After testing, one of them will be selected to become part of the RFC.

The catalytic hydrogen cooker was developed in our institute within the framework of the research on catalytic combustion /17/. The cooker provides power output of 2 kW and there are technologies available to combust hydrogen with oxygen or with air. The catalytic hydrogen oxygen burner constitutes an overall closed system with water rejection, while the hydrogen air burner operates in ambient air without any controlled condensation. Therefore the efficiency is lowered, but the air burner achieves much higher specific power densities resulting in reduced volume requirements.

#### RFC SYSTEM VARIATIONS FOR TERRESTRIAL SOLAR INSTALLATIONS

The RFC arrangement generally considered for space applications consists of a completely closed system exchanging no mass with the ambient, but energy only. The electrolyser and each of the gas consumers are connected to the hydrogen, to the oxygen, and to the water tank, Fig. 4 a.

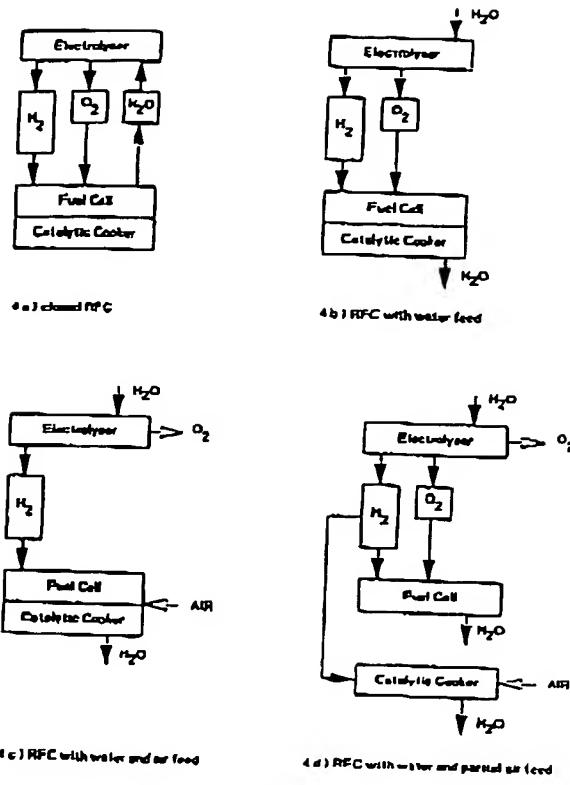


Fig. 4

The concept is attractive because the system is totally sealed, but on the other hand disadvantages have to be viewed, such as reduced energy density due to electrolyte dilution in alkaline systems or difficulties in the gas and heat management.

On earth the aspect of sealed operation is not as important as in space and therefore, the design of the RFC may be simplified by leaving out the water storage and refeeding to the RFC the water being lost during discharge, Fig. 4 b.

The most simple RFC configuration abandons the water tank as well as the oxygen cylinder, Fig. 4 c. In the electrolysis mode the oxygen is blown off to the ambient air and during discharge the fuel cell or the catalytic cooker are using air as oxidiser. The number of components is reduced by this concept, but as a consequence the system efficiency decreases. This occurs because the performance of the fuel cell is lowered when running on hydrogen-air instead of hydrogen-oxygen. Additionally, some other system aspects concerning the fuel cell change for the worse.

The RFC concept we follow is illustrated in Fig. 4 d, which differs from the others in so far that only a certain part of the oxygen is stored in gas tanks which is sufficient to operate the fuel cell on hydrogen-oxygen. By that measure the volume of the oxygen cylinders becomes smaller, the fuel cell losses are reduced, and the efficiency of the RFC increases.

## CONCLUSIONS

RFCs are promising devices for energy storage. There is a broad variety of technologies and RFCs constitute the link from secondary batteries to hydrogen energy systems.

Actually it is problematic to realize terrestrial solar stand-alone installations, due to the lack of reasonable seasonal storage. In future hybrid storage systems consisting of lead-acid battery and RFC will become a very attractive tool for system engineers. The RFCs have the potential to compete with other storage batteries provided that the membrane cells will become cheaper and perhaps reversible.

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